where n is the number of resonances observed; the sample is presumed to be random.

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¹C. E. Porter and R. G. Thomas, Phys. Rev. **104**,

483 (1956). See also C. E. Porter and N. Rosenzweig, Ann. Acad. Sci. Fennicae (Physica) No. A44 (1960).

²J. M. Blatt and V. F. Weisskopf, Theoretical Nuclear Physics (John Wiley & Sons, Inc., New York, 1952), p. 386; D. L. Hill and J. A. Wheeler, Phys. Rev. **89**, 1102 (1953).

DIRECT MEASUREMENT OF μ^- -MESONIC MOLECULE FORMATION RATES IN LIQUID HYDROGEN

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It has been shown¹ that if a few parts per million of Ne are dissolved in deuterated hydrogen, the following reactions are likely to occur:

The (μp) [or (μd)] binding energy is much smaller than the (μNe) ground-state binding energy. Therefore, transfer to an excited (μNe) state may occur. Mesonic de-excitation x rays characteristic of the Ne mesonic atom are then expected.

We are reporting experimental evidence here for $2p-1s$ transition mesonic x rays of 214 keV from Reactions (1a) and (1b) obtained by dissolving neon in deuterium-free hydrogen and deuterium-hydrogen mixtures, respectively. Our re-

sults indicate that Reaction (1) leading to excited states is compatible with 100% of the cases.

The time distribution of these γ rays makes possible a direct measurement of the speed of $(p\mu p)$ and $(p\mu d)$ molecule formation.

The experimental apparatus is shown in Fig. 1. Negative muons ($\sim 3000/\text{sec}$) from the μ^- channel² are brought to rest in an 8-liter liquid hydrogen target made out of Mylar. The synchrocyclotron was operated with stochastic extraction³ and duty cycle $\sim 30\%$. Hydrogen was purified by passing it through cold traps, silica gel, and Deoxo purifiers, before entering in a palladium leak purifier.⁴

Total capture rate experiments performed in a liquid hydrogen bubble chamber⁵ have shown that the over-all contamination of gases with $Z > 2$ obtained with such a purifier is certainly less

FIG. 1. Schematic layout of experimental arrangement and simplified block diagram of the electronics.

than 10^{-8} , assuring negligible perturbation of the (μp) and (μd) lifetimes due to transfers to impurities. In order to prevent neon from freezing (melting point 24°K), it was greatly diluted with purified hydrogen before being injected into the target. For such a reason we cannot state how much of the injected neon has actually been dissolved into the liquid hydrogen.

The 214-keV mesonic x rays from neon are detected by a 12-cm long, 12-cm diameter NaI crystal. The energy lost in the NaI crystal as well as the time interval between the arrival of the muon and the emission of the γ ray were analyzed by two 256-channel TMC pulse-height analyzers and punched in digital form on paper tape. The tapes were then read by an electronic computer and events ordered in a 128×256 matrix. In order to reject γ rays from captures and from decay-electron bremsstrahlung, a late decay electron was required in counter 6.

To determine the over-all probability of detection as well as the energy calibration and the energy and time resolution of the apparatus, a separate measurement of $2p-1s$ mesonic x rays from Ne was made, by replacing the liquid hydrogen of the target with neon gas at liquid nitrogen temperature. Frequent further checks were made with mesonic x rays from Al and radioactive sources.

Measurements were taken in the following sequence:

- (i) With the target full of neon-free hydrogen,

FIG. 2. Schematic representation of possible reaction paths after formation of (μp) : (a) in deuterium-free hydrogen-neon mixture; (b) in hydrogen-neon mixture containing deuterium.

data were taken in order to determine eventual structure of the background.

(ii) Then various amounts of neon were added, monitoring the fraction of negative muons transferred from the (μp) [or (μd)] atom to the neon both by the decrease of the number of decay electrons and by the change of the μ^- lifetime. In fact, the capture probability of a μ^- is negligibly small for hydrogen, and (0.33 ± 0.05) in the case of neon.⁶

For the (μp) lifetime, the target was filled up with deuterium-free liquid hydrogen. The sequence of events occurring after adding neon are as follows⁷: (i) The negative muon is slowed down and captured in a $1s$ orbit. Exchange collisions rapidly convert all the (μp) system into the singlet

Table I. Summary of results.

Process	D ₂ concentration	Amount of neon added	Measured fraction of μ^- transferred to neon ^a	Rate of mesonic-molecule formation ^b	2p-1s mesonic x ray per transfer to neon ^c
$(\mu p) + p \rightarrow (p\mu p)$	≤ 8 ppm ^d ~ 3 ppm ^e	28.5 ppm	$(5.1 \pm 1.0) \%$	$\lambda_{pp} = (2.4 \pm 0.6) \times 10^6 \text{ sec}^{-1}$	0.85 ± 0.26
	≤ 8 ppm ^d ~ 3 ppm ^e	114 ppm	$(14 \pm 2.5) \%$	$\lambda_{pp} = (2.04 \pm 0.12) \times 10^6 \text{ sec}^{-1}$	1.07 ± 0.29
$(\mu d) + p \rightarrow (p\mu d)$	4060 ppm	15.75 ppm	$(17 \pm 3) \%$	$\lambda_{pd} = (4.96 \pm 0.35) \times 10^6 \text{ sec}^{-1}$	1.03 ± 0.28
	460 ppm	31.5 ppm	$(32 \pm 5) \%$	$\lambda_{pd} = (5.46 \pm 0.52) \times 10^6 \text{ sec}^{-1}$	0.83 ± 0.22
	10 060 ppm	31.5 ppm	$(32 \pm 5) \%$	$\lambda_{pd} = (5.90 \pm 0.60) \times 10^6 \text{ sec}^{-1}$	1.01 ± 0.26

^aThe fraction of μ^- transferred to Ne is evaluated from the decrease of decay electrons assuming that the probability of a μ^- nuclear capture in Ne is 0.33 ± 0.05 . See reference 6.

^bRates are obtained from experimental decay times (see Fig. 2) correcting for Ne and D₂ presence.

^cYields are calculated from the known value of the over-all efficiency $(4.6 \pm 0.9) \times 10^{-4}$ as measured filling up the target with Ne gas.

^dThis upper limit has been obtained by looking for fusion γ rays from reaction $(p\mu d) \rightarrow \text{He}^3 + \mu + \gamma$.

^eResult of spectroscopic analysis of the manufacturer.

state. (ii) The thermal neutronlike (μp) atom then either forms a hydrogen molecular ion (rate λ_{pp}) or loses the μ^- to neon (rate $c_{\text{Ne}}\lambda_{\text{Nep}}$). No transfer from the meson-molecule to neon is possible owing to its positive charge. These processes are represented symbolically in Fig. 2(a).¹

For the (μd) lifetime, the target was filled with "natural" liquid hydrogen to which 0.5% of deuterium was added. Here we can sketch the sequence shown in Fig. 2(b).

Results are summarized in Table I and Fig. 3. Our direct measurement of λ_{pp} and λ_{pd} confirms the values obtained by comparing the time dependence of fusion γ rays at different D_2 concentrations.⁸ Such time dependence remains unchanged under the exchange of the value of λ_{pd} and λ_f . In a recent work, Dzhelepov et al.,⁹ with the help of a diffusion cloud chamber at room temperature, have indicated the solution $\lambda_f \gg \lambda_{pd}$. Our results indicate instead that $\lambda_{pd} \gg \lambda_f$ in agreement with liquid deuterium bubble chamber results.¹⁰ In fact, the alternative $\lambda_f \gg \lambda_{pd}$ would imply that⁸ $\lambda_{pd} = (0.26 \pm 0.03) \times 10^6 \text{ sec}^{-1}$, in clear disagreement with our results.

Combining our value of $\lambda_{pp} = (2.04 \pm 0.14) \times 10^6 \text{ sec}^{-1}$ with the known⁹ ratio $(\lambda_{pp} + \lambda_0)/\lambda_e = (1.06 \pm 0.11) \times 10^4$ (λ_0 = muon decay rate), we can deduce $\lambda_e = (2.34 \pm 0.28) \times 10^{10} \text{ sec}^{-1}$ to be compared with the theoretically predicted value⁷ $\lambda_e = 1.4 \times 10^{10} \text{ sec}^{-1}$.

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¹M. Schiff, thesis, University of Chicago, Report No. 351, 1961 (unpublished); Nuovo cimento **22**, 66 (1961).

²A. Citron, C. Delorme, F. J. M. Farley, L. Goldzahl, J. Heintze, E. G. Michaelis, M. Morpurgo, and H. Øverås, *Proceedings of the International Conference on Instrumentation for High-Energy Physics, Berkeley, California, September, 1960* (Interscience Publishers, Inc., New York, 1961), p. 286.

³L. Dick and J. Vermeulen (to be published).

⁴Engelhard Industries, Inc., Chemical Division, Newark, New Jersey.

FIG. 3. (a) Counting rate $n(t)$ as a function of time relative to muon stopping of 214-keV mesonic x rays from the reaction $(\mu d) + \text{Ne} \rightarrow (\mu \text{Ne}) + d$. Data are for a fraction of μ^- transferred to Ne equal to $(17 \pm 3)\%$. The solid line represents the result of a least-squares fit of the experimental points [decay time = (153 ± 10) nsec]. (b) The same time distribution as in (a) before adding Ne. (c) Time distribution and least-squares fit for the reaction $(\mu p) + \text{Ne} \rightarrow (\mu \text{Ne}) + p$. Fraction of μ^- transferred to Ne equal to $(14 \pm 2.5)\%$ [decay time = (340 ± 15) nsec]. (d) The same time distribution as in (c) before adding Ne. Data have been normalized, but otherwise uncorrected.

⁵E. Bertolini, A. Citron, S. Focardi, G. Gialanella, A. Mukhin, C. Rubbia, and F. Saporetto, *Proceedings of the International Conference on High-Energy Nuclear Physics, Geneva, 1962* (CERN, Geneva, Switzerland, to be published).

⁶We have taken the value from reference 1.

⁷For a comprehensive review of references on the theoretical as well as experimental work done on the subject, see Y. B. Zel'dovich and S. S. Gershtejn, *Uspekhi Fiz. Nauk* **71**, 581 (1960) [translation: *Soviet Phys. - Uspekhi* **3**, 593 (1961)].

⁸E. Bleser, L. Lederman, J. Rosen, J. Rothberg, and E. Zavattini, *Phys. Rev. Letters* **8**, 128 (1962); S. Focardi, G. Gialanella, and C. Rubbia (to be published).

⁹V. P. Dzhelepov, P. F. Yermolov, Ye. A. Kushnirenko, V. I. Moskalev, and S. S. Gershtejn (to be published).

¹⁰J. G. Fetkovich, T. H. Fields, G. B. Yodh, and M. Derrick, *Phys. Rev. Letters* **4**, 570 (1960).